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TUNGSTEN AS A SLIPRING MATERIAL FOR USE WITH GALLIUM LUBRICATION IN ULTRAHIGH VACUUM

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16. Abstract

Low speed (132 mm/min) gallium lubricated ground tungsten against tungsten (hemisphere on disk) slipring assembly experiments in vacuum showed that, although film formation appeared to be good, gallium bonding to the tungsten surface was mechanical (trapping in surface grooves). Gallium lubrication increased the hemisphere wear by a factor of 4 and decreased disk surface damage compared to a similar dry experiment. The coefficient of friction was reduced from ~0.5 (dry) to ~0.28 (gallium lubricated). The range of observed electrical noise value was decreased from 4.5 to 125.0 mΩ PTP (dry) to 0.005 to 1.6 mΩ PTP (gallium lubricated). Removal of disk surface grooves by etching (to prevent gallium trapping) resulted in high electrical noise.

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TUNGSTEN AS A SLIPRING MATERIAL FOR USE WITH GALLIUM LUBRICATION IN ULTRAHIGH VACUUM

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SUMMARY

Ten-hour experiments using both dry and gallium lubricated slipring assemblies consisting of a tungsten hemisphere contacting the surface of a ground tungsten disk in a vertical plane were made in vacuum (10^{-9} to 10^{-10} torr) at a speed of 132 millimeters per minute (1 rpm) using a load of 100 grams. The gallium was applied to the surface of the disk by swabbing in atmosphere. The use of gallium resulted in a reduction in the coefficient of friction f from $\overline{f} \sim 0.50$ (dry) to $\overline{f} \sim 0.28$. Gallium lubrication increased the hemisphere wear from 3.6×10^{-4} cubic millimeter (dry) to 13.4×10^{-4} cubic millimeter but decreased surface damage to the disk to a point where it was barely detectable with a surface profilimeter at a vertical magnification of 10 000. The range of contact noise values observed with gallium lubrication (0.005 to 1.60 mΩ peak to peak) were much below those values observed in a similar dry experiment (4.5 to 125.0 mΩ peak to peak). Visual observation revealed that most of the gallium was swept from the wear track during the gallium lubrication experiments. Examination of the wear track after the experiment revealed minute amounts of gallium trapped in surface grooves. The conclusion was made that gallium adhesion to a ground tungsten surface was mechanical. A separate experiment was made using a tungsten disk that was etched in a sodium hydroxide solution to remove the surface grooves produced by the grinding process. Visual observation revealed that the gallium film was displaced from the wear track during the first revolution resulting in a marked increase in electrical contact noise after the first revolution.

INTRODUCTION

Experiments using liquid gallium as a contacting slipring lubricant in vacuum have resulted in slipring assemblies which show very low contact resistance and low electrical noise (refs. 1 and 2). However, the very good electrical results are obtained at the expense of increased wear rates. The amount of wear observed in using gallium as a lubricant for several slipring materials has exceeded the wear observed in using these same materials run dry. The previous experimental results show that, so far, corrosive wear is the most critical problem encountered in the use of gallium as a lubricant. In view of the serious corrosion problem, it is desirable to investigate elemental metals which are "corrosion resistant" to gallium. Experiments should be made to determine whether gallium corrosion is also a problem with these materials if they are used for gallium lubricated slipring operation in vacuum.

Available gallium corrosion data show that tungsten has good corrosion resistance to liquid gallium up to 800° C (ref. 3). It would also be an effective slipring material because of its good electrical conductivity ($\sim 5.8\ \mu\Omega$-cm, ref. 4) and high tensile strength. Tungsten's high tensile strength makes it a very attractive material for use in high voltage slipring systems where electrostatic stresses are high. Tungsten's high work function (4.55 eV) is also an asset under high voltage conditions where field emission is a contributing factor in the electrical breakdown of gaps between metal electrodes in high vacuum (ref. 5). On the basis of this combination of properties, tungsten should be a good, wear resistant slipring material when used with gallium lubrication in vacuum. Its mechanical and electrical properties should make it a useful slipring material in both high voltage and high current applications.

The objective of this investigation was to determine the coefficient of friction, wear, contact resistance, and electrical noise of a tungsten against tungsten slipring assembly both dry and lubricated with a gallium film. A slipring assembly consisted of a 4.76-millimeter-radius hemispherically tipped rod (brush) contacting the flat surface of a 50.8-millimeter outside diameter disk (slipring). The slipring was run at a speed of 132 millimeters per minute (1 rpm) under a load of 100 grams in a vacuum of 10^{-10} torr. Slipring current was 33 milliamperes, 40 hertz.

APPARATUS

Vacuum System

An ultrahigh vacuum system with double gold O-ring sealed flanges was used for all of the slipring experiments. The vacuum chamber is separated into two sections that share a common wall. One section contains the support bearings for the drive shaft. The slipring experiments are made in the remaining section. The drive shaft is brought into the slipring section of the vacuum chamber through a close clearance annulus in the dividing wall. This arrangement forms a molecular seal which isolates the support bearings from the slipring assembly. Each section of the vacuum chamber is pumped by its own ion pump. A liquid nitrogen cooled titanium sublimation pump is also available to assist in pumping the slipring section.

Rotary motion is transmitted into the vacuum chamber by a pair of 20-pole circular magnets which face each other through a thin stainless-steel diaphragm mounted in one of the vacuum flanges. Drive power is supplied by a tachometer stabilized direct current motor which drives the external magnet through a 900-to-1 ratio gearbox.

Chamber pressure is measured with a triggered discharge gage.

Contact Resistance Measuring Circuit

Contact resistance of the slipring assembly is measured by the four-terminal method using a commercial alternating current milliohmmeter. One voltage and one current connection from the milliohmmeter are connected directly to the hemisphere. The remaining current and voltage leads are connected to the opposite ends of a copper cup containing liquid gallium. The disk is mounted on an oxygen-free high-conductivity (OFHC) copper spindle that is completely insulated from the drive shaft. A ring machined into the opposite end of the spindle and immersed in the liquid gallium completes the electrical circuits to the slipring assembly.

Frictional Force Measurement System

The hemisphere is mounted in an insulated aluminum block that is affixed to one end of a cantilever beam. The friction force that is developed between the hemisphere and disk bends the beam. Beam displacement is sensed by a capacitance probe mounted at a right angle to the direction of bending. The output of the probe control is calibrated in grams force.

The vacuum system, contact resistance measuring circuit, and frictional force measurement assembly are described in further detail in references 1, 2, and 6.

Preparation of Specimens

The disk (slipring) construction is shown in figure 1. It consists of a flat tungsten disk 3.2 millimeters thick with a 50.8~ millimeter outside diameter bolted to an OFHC copper backing plate that is machined to fit the test spindle. This approach was used to simplify the machining of the tungsten sheet. The tungsten disk (slipring) was electrical discharge machined from a 3.2-millimeter-thick tungsten sheet and ground to produce parallel faces with an 8 rms finish. The hemispherically tipped rod (brush) was ground from a 9.5-millimeter outside diameter tungsten rod. Rod and plate purity was 99.95 percent minimum. All specimens were detergent cleaned and rinsed in absolute alcohol prior to use.

PROCEDURE

The following experiments were performed: (1) ground tungsten against ground tungsten (dry), 10 hours (for reference data), (2) ground tungsten against ground tungsten with a gallium film, 10 hours, and (3) electroetched tungsten against electroetched tungsten, 5 minutes. During the experiments, measurements of friction force and contact resistance were made. The contact resistance was measured with a commercial ac milliohmmeter. Contact noise was determined by taking the difference between the highest and lowest contact resistance readings that occurred during a 1-minute interval around a given time. Contact noise is reported as milliohms peak to peak (PTP). Wear was determined by measuring the diameter of the wear scar on the tip of the hemisphere and calculating the wear volume.

Gallium (99.999 percent purity) was applied to one face of a tungsten disk by means of a cotton swab in atmosphere. Gallium was swabbed onto the face of the disk in the form of an annulus that covered the wear track zone. A forceful scrubbing action was necessary to get the gallium to form a film on the surface of the tungsten disk (a characteristic similar to that of OFHC copper used in earlier experiments). The weight of gallium used was 0.65 gram. The gallium displayed no tendency to wet the area beyond that scrubbed by the cotton swab. No gallium was applied to the hemisphere. All experiments were made with the lubricated face of the disk in the vertical plane.

RESULTS

Tungsten Against Tungsten (Dry)

The reference data obtained from the dry tungsten against tungsten experiment showed a high coefficient of friction and relatively high electrical noise. The amplitude of the friction data was very large ($0.1 < \bar{f} < 1.1$) making the raw data very difficult to interpret. Consequently, it was decided to obtain the highest and lowest values that occurred during a 1-minute interval around a point in time and plot these values rather than an average value against time. The resulting graph is shown in figure 2. It shows that the coefficient of friction is generally high, occasionally reaching values of one or more. The average coefficient of friction increased later in the experiment as the contacting surfaces were cleaned of contaminants as a result of the continuous mechanical abrasion.

The electrical contact noise is shown in figure 3. High peak values of contact resistance (up to 125 mΩ) were generally concurrent with rapid decreases in the coefficient of friction.

Some representative high peaks of contact resistance and their relationship to the coefficient of friction are shown in figure 4. Many similar peaks occurred during the first few hours of running time which suggests that they are a result of the breaking up of insulating surface films and the gradual development of a semistable contact area. The incidence and magnitude of the contact resistance peaks greatly decreased as the experiment accumulated running time. Nevertheless, the dry tungsten slipring assembly remained electrically noisy (>5 mΩ PTP) throughout the duration of the experiment.

Contact resistance values for the dry tungsten against tungsten slipring assembly were relatively high and ranged from approximately 8 to 15 mΩ. Some contact resistance values at specific time increments are shown in table I.

The 10-hour hemisphere wear volume was approximately 3.6×10^{-4} cubic millimeter which corresponds to a wear rate of about 4.55×10^{-9} cubic millimeter per millimeter of sliding.

A surface profile trace across the wear track on the dry tungsten disk (fig. 5) showed a significant amount of surface damage. This trace will be compared to others taken after experiments using gallium as a lubricant to ascertain if the use of gallium results in increased wear on the disk's surface as it generally does on the tips of the hemispheres (refs. 1 and 2).

Tungsten Against Tungsten With Swabbed Gallium Film

A swabbed gallium film on the surface of the tungsten disk resulted in a reduction of both the coefficient of friction (fig. 6, plotted as in fig. 2) and electrical noise (fig. 7) of the tungsten hemisphere against tungsten disk slipring assembly.

The coefficient of friction had a value of approximately 0.25 near the beginning of the experiment but tended to increase slightly as the experiment progressed. The amplitude of the coefficient of friction data was greatly reduced as can be seen by comparing figure 6 with figure 2.

High contact resistance peaks that were prevalent throughout the duration of the dry experiment were completely absent in the gallium film experiment. In addition, all values of contact noise obtained with the gallium film (0.005 to 1.60 mΩ PTP, fig. 7) were less than the lowest value obtained in the dry experiment (4.5 mΩ PTP).

If the contact noise is used as a guide, the gallium lubricated tungsten slipring assembly required about an 80-minute period for contact noise values to stabilize (break-in period). After the break-in period, the range of fluctuations in observed contact noise values were small (<0.065 mΩ PTP). The lowest value of contact noise observed (0.005 mΩ PTP) is about three times larger than the contact noise observed in earlier gallium lubricated OFHC copper slipring assembly experiments (ref. 2).

A plot of contact resistance against time for the gallium lubricated tungsten slipring assembly is shown in figure 8. Contact resistance values ranged from a high of 1.85 milliohms near the beginning of the experiment (6 min running time) to a low of 0.11 milliohm near the end of the experiment (550 min). The contact resistance stabilized concurrently with the contact noise, and after stabilization, steadily decreased to the end of the 10-hour experiment.

Visual observation of the gallium film on the tungsten disk during the experiment showed that the gallium film was being swept from the wear track by the traversing of the hemisphere leaving what appeared to be a gallium-free annulus on the surface of the tungsten disk. If the gallium had been completely swept from the wear track, the coefficient of friction and electrical contact noise should have risen to values comparable to those observed in the dry experiment. However, the experimental data showed that the coefficient of friction (fig. 6) rose only slightly and that the electrical contact noise (fig. 7) actually decreased even as the gallium was being swept from the contact area. The experimental data can lead only to the conclusion that not all of the gallium was swept from the contact area. The slight rise in the coefficient of friction indicates that sufficient gallium was swept from the contact area to permit some contact of the tungsten surfaces. Postexperiment microscopic examination of the wear track on the tungsten disk showed that gallium was present in the wear track. Closer examination revealed that the gallium was being held in surface grooves which were a product of the specimen finishing process. A photomicrograph of a portion of the wear track is shown in figure 9. Apparently, the minute amount of gallium trapped in the grooves was sufficient to influence both the coefficient of friction and the electrical contact noise.

A surface profile trace (fig. 10) across the wear track on the surface of the tungsten disk shows that no surface damage is visible at a vertical magnification of 10 000. To eliminate the possibility of the gallium masking any surface damage that would otherwise be detectable by the surface profilimeter, refer again to figure 9. The photomicrograph shows the original grinding marks still present in the wear track (running at about a 20° angle to the path of the hemisphere) which substantiates the data produced by the surface profilimeter.

A photograph of the tungsten disk specimen after the 10-hour experiment is shown in figure 11. The wear track is clearly visible as a result of most of the gallium being swept from it. A careful examination of the photograph will reveal some gallium trapped in surface grooves (pointed out in the photograph) which are running at an angle to the wear track. Also shown is a glob of liquid gallium which, under the force of gravity, has migrated to the bottom of the disk.

Wear volume on the tip of the hemisphere was 13.4×10^{-4} cubic millimeter which corresponds to a wear rate of 17×10^{-9} cubic millimeter per millimeter of sliding. The hemisphere wear rate in the presence of gallium is about four times greater than when the tungsten surfaces are dry although the damage to the surface of the disk is much less.

Smooth Tungsten Disk With Swabbed Gallium Film

To determine the importance of the surface grooves on a tungsten disk in a gallium lubricated tungsten slipring assembly, an experiment was performed using a tungsten disk that was etched in a sodium hydroxide (NaOH) solution to obliterate the surface grooves. If the electrical performance is dependent on gallium being trapped in surface grooves, then the electrical performance of a slipring assembly using a relatively smooth tungsten disk should be poor.

The etched surface of the tungsten disk was swabbed with a gallium film. Film formation appeared to be good. All conditions for this experiment, except disk surface finish, were the same as for the other tungsten-gallium experiments.

Visual observation of the first few revolutions of the disk revealed that the gallium film was swept from the wear track during the first revolution. A plot of electrical contact noise against time for this experiment is shown in figure 12. It shows that the contact noise was relatively low during the first revolution when the gallium was being swept from the track. During the second revolution, when most of the gallium was absent from the wear track, the electrical contact noise increased rapidly.

During the third revolution, the contact noise continued to increase. The contact noise during the next few revolutions was off-scale on the instruments in use. At the end of the third revolution, the contact noise (2.04 mΩ PTP, fig. 12) was already higher than the highest value observed during the earlier gallium film experiment (1.60 mΩ PTP, fig. 7) where grooves were present to trap the gallium. The rapid rise in contact noise shows that the gallium was more completely swept from the wear track when grooves were absent.

A photograph of the tungsten disk used in this experiment is shown in figure 13. It is easily seen that the gallium film is not continuous in the wear track. Those portions of the wear track that are covered by a gallium film are a result of the bridging of the wear track by the gallium which was initially displaced to either side of the track. The bridging occurred as a result of handling the specimen during examination and photography. The handling of the disk caused the gallium on either side of the track to spill over the track and coalesce with the gallium on the other side thus giving the appearance of gallium adherence in the track.

The results of the three slipring experiments are summarized in table I.

DISCUSSION

Comparison with Previous Results

The electrical data from the gallium lubricated tungsten slipring experiment showed that both the contact resistance and contact electrical noise were higher than expected by an order of magnitude based on the results of previous experiments with gallium (refs. 1 and 2). It was expected that the electrical results would be similar to those obtained from the experiments that used OFHC copper or a beryllium-copper alloy as the gallium lubricated slipring material. The reason for the expected similarity of results was that the formation of a gallium film on the OFHC copper, beryllium-copper alloy, and tungsten slipring materials appeared similar. The difference in experimental results show that the single requirement of similar gallium film formation is an insufficient criterion for predicting good electrical slipring performance. An explanation for the difference in results will aid in the possible formulation of a general criteria that will account for all of the results up to the present time. Ultimately, a criteria may be evolved that will lead to useful predictions of gallium lubricated electrical slipring performance using various slipring materials.

It is becoming apparent that the mere use of gallium in combination with any slipring material will not guarantee good results. The slipring material will have to be carefully chosen to take advantage of a desired characteristic because the data available at present shows that there is no one slipring material that possesses <u>all</u> of the desired characteristics.

Bonding of Gallium to Tungsten

Observation of the face of the tungsten disk during the experiments showed that a large portion of the gallium film was displaced from the wear track by the traversing of the hemisphere. Microphotographs taken of the wear track zone (figs. 9 and 13) show that the gallium film is largely absent in the wear track zone. The absence of a gallium film is reflected in a slight rise in the average coefficient of friction during the 10-hour gallium lubricated tungsten slipring assembly experiment (fig. 6). It appears that the slight amount of gallium present is sufficient to prevent the coefficient of friction from rising to that observed for dry tungsten sliding against tungsten (fig. 2). However, the small amount of gallium remaining in the wear track zone is insufficient to fill in all of the gaps and voids in the contact zone and relatively higher values of contact resistance result. This occurs because the real area of contact is smaller than that which would occur if the voids and gaps were completely filled.

In the case of the OFHC copper and beryllium-copper alloy slipring experiments, the gallium film remained in the contact zone in sufficient quantities to fill in more completely the gaps and voids in the contact zone. This action resulted in a larger actual contact area and consequently lower values of contact resistance.

The difference in the electrical performance between the tungsten and OFHC copper or beryllium-copper alloy slipring assemblies lies in the amount of gallium that remains in the wear track zone during sliding. The persistance of a lubricating film between two sliding surfaces under load is highly dependent upon the strength of the bond between the lubricant and the surface to be lubricated. If the bonding is strong (e.g., chemical reaction), shear will occur in the lubricant and the lubricant will be more difficult to dislodge from the surface. If the bond is weak (e.g., mechanical), shear will probably occur between the lubricant and the surface to be lubricated and it will be less difficult to dislodge the lubricant from the surface and displace it from the wear track zone.

Since the gallium film did not persist in any great quantity in the wear track zone on the tungsten disk, the bonding was poor and suggestive of mechanical bonding. Conversely, the gallium film persisted in quantity in the case of OFHC copper and the beryllium-copper alloy experiments, until the termination of the experiments at 100 hours. This behavior indicates a very strong bond suggestive of chemical bonding or surface reaction.

Bonding, then, is the key to the difference in the electrical performance between the tungsten and OFHC copper or beryllium-copper alloy slipring assemblies. This factor must be included together with film formation characteristics in any modified criteria concerning the predicted electrical performance of gallium lubricated slipring assemblies.

Evidence of a surface reaction between a gallium film and an OFHC copper surface has been presented in reference 2. It remains to be shown whether there is a lack of surface reaction between gallium and a tungsten surface.

High Temperature Gallium-Tungsten Reaction Experiment

Since visible evidence for a copper gallium reaction was obtained at a temperature of approximately 120° C, it was decided to subject a gallium-tungsten combination to high temperatures to see if a visible reaction would occur between these two materials.

The experiment consisted of a tungsten boat (evaporation source) with a thermocouple attached that contained a drop of gallium. The boat could be resistance heated under vacuum (10^{-6} torr) to temperatures in excess of 1100° C.

At boat temperatures up to 675° C (approximately the temperature at which tungsten trioxide (WO_3) volatilizes, ref. 4), the gallium remained in the shape of a ball. As the temperature was increased, the gallium began to spread out in a portion of the boat near the center. A temperature of approximately 800° C was held for about 5 minutes before allowing the boat to cool. After cooling, the bulk of the gallium was emptied. The small amount of gallium remaining in the boat was rather easily wiped out with a paper towel. The results of this simple experiment show that the adhesion of gallium to tungsten is rather poor despite the high temperature used in an effort to obtain a reaction. The appearance of the interior of the boat suggested that little or no surface reaction had taken place and that the bonding which did occur was mechanical. If the adhesion is poor at high temperatures, it follows that adhesion would also be poor near room temperature.

It appears that the bonding between the gallium film is mechanical in nature and that, because of the low strength of this type of bond, gallium cannot be retained on a smooth tungsten surface in a sliding condition. Since the bonding is mechanical, the methods for enhancing this type of bond, such as roughening or grooving of the surface, must be used to retain gallium in the sliding area. This requirement was inadvertently fulfilled in the gallium film experiment discussed earlier.

The advantage of using tungsten as a slipring material with gallium lubrication is its corrosion resistance to gallium. However, its corrosion resistance also results in poor bonding of the gallium to the surface due to a lack of surface reaction. The retention of gallium on a tungsten surface by mechanical means can result in a good slipring assembly, but the contact resistance and electrical noise can never be as low as those obtained with slipring materials which exhibit strong gallium bonding. This is simply a result of more gallium being retained in the contact area when the bonding is strong (surface reaction) than could be retained by mechanical bonding on a rough surface.

SUMMARY OF RESULTS

Low speed (132 mm/min) sliding electrical contact experiments in vacuum using both dry and gallium lubricated ground tungsten slipring assemblies (pin on disk, face of disk in vertical plane) were made and the following results were obtained:

1. The dry tungsten slipring assembly exhibited a high coefficient of friction (at times greater than one) and rapid decreases in the coefficient of friction that greatly increased the electrical contact noise (at one time to 125 mΩ peak to peak).

2. The use of a gallium film as a lubricant for a tungsten slipring assembly reduced the coefficient of friction to approximately 0.28 and eliminated what appeared to be a stick-slip action.

3. The use of a gallium film as a lubricant for a tungsten slipring assembly reduced the lowest observed electrical noise value (0.005 mΩ peak to peak) by a factor of 900 below the lowest value observed in the dry experiment (4.5 mΩ peak to peak).

4. The use of a gallium film as a lubricant for a tungsten slipring assembly eliminated all high contact resistance peaks that were observed in the dry experiment.

5. The use of a gallium film as a lubricant for a tungsten slipring assembly resulted in substantially decreased surface damage in the wear track of the tungsten disk as compared to that obtained in the dry experiment.

6. The use of a gallium film as a lubricant for a tungsten slipring assembly increased the wear of the hemisphere (13.4×10^{-4} mm^3) by a factor of 3.7 compared to that obtained in the dry experiment (3.6×10^{-4} mm^3).

7. Adhesion of the gallium film to a tungsten surface was very poor and was retained in the wear track area under the action of sliding only by being trapped in the surface grooves that were produced by the machining process.

8. Removal of the surface grooves on a tungsten disk by electroetching in sodium hydroxide resulted in the gallium film being swept from the wear track after one revolution of the disk with a subsequent large increase in electrical noise from 0.06 milliohm peak to peak after the first revolution to 2.04 milliohms peak to peak after the third revolution.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 30, 1970,
129-03.

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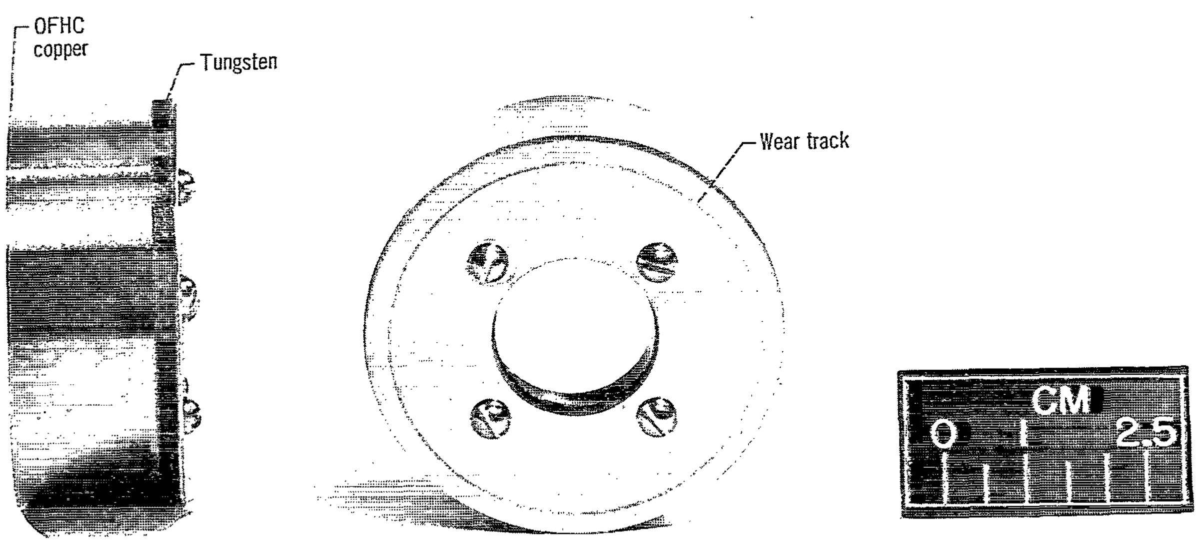
TABLE I. - SUMMARY OF RESULTS OF TUNGSTEN

SLIPRING ASSEMBLY EXPERIMENT

[Disk (slipring), tungsten; hemisphere (brush), tungsten; contact current: 33 mA, 40 Hz; surface wetting after slight scrubbing.]

Run time	10 hr	10 hr	5 min
Lubricant	None	Gallium film	Gallium film
Disk surface condition	Ground	Ground	Etched smooth
Range of coefficient of friction	0.1 to 1.1	0.11 to 0.40	(a)
Electrical contact noise, mΩ peak to peak at -			
1 min	-----	1.600	0.07
2 min	54.00	0.800	0.74
3 min	50.00	0.350	2.04
10 min	49.00	0.420	(b)
100 min	7.00	0.062	(b)
600 min	9.00	0.010	(b)
Contact resistance, mΩ at -			
1 min	12.90	0.876	0.15
2 min	9.00	0.674	1.10
3 min	11.00	0.585	2.25
10 min	14.00	1.460	(b)
100 min	9.00	0.233	(b)
600 min	10.50	0.120	(b)
Hemisphere wear, mm^3	3.64×10^{-4}	13.4×10^{-4}	(a)

[a]Not measured.
[b]Experiment terminated.



C-70-1057

Figure 1. - Tungsten slipring specimen.

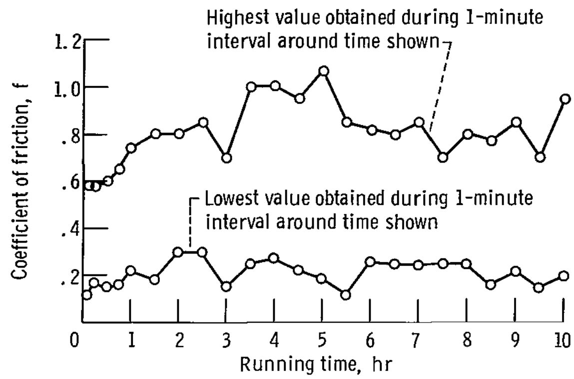


Figure 2. - Coefficient of friction against time for a tungsten disk running against a tungsten hemisphere. No lubrication; speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

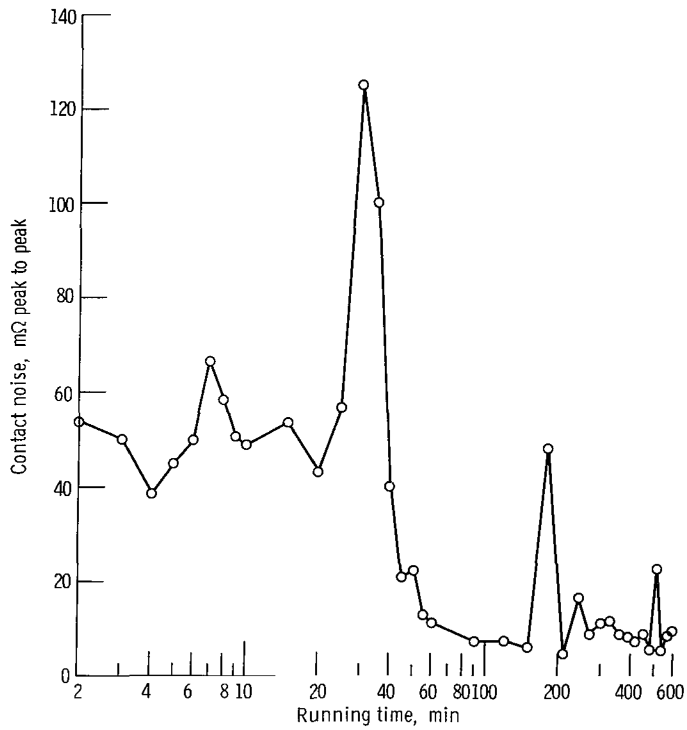


Figure 3. - Contact noise against time for a dry tungsten disk running against a tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

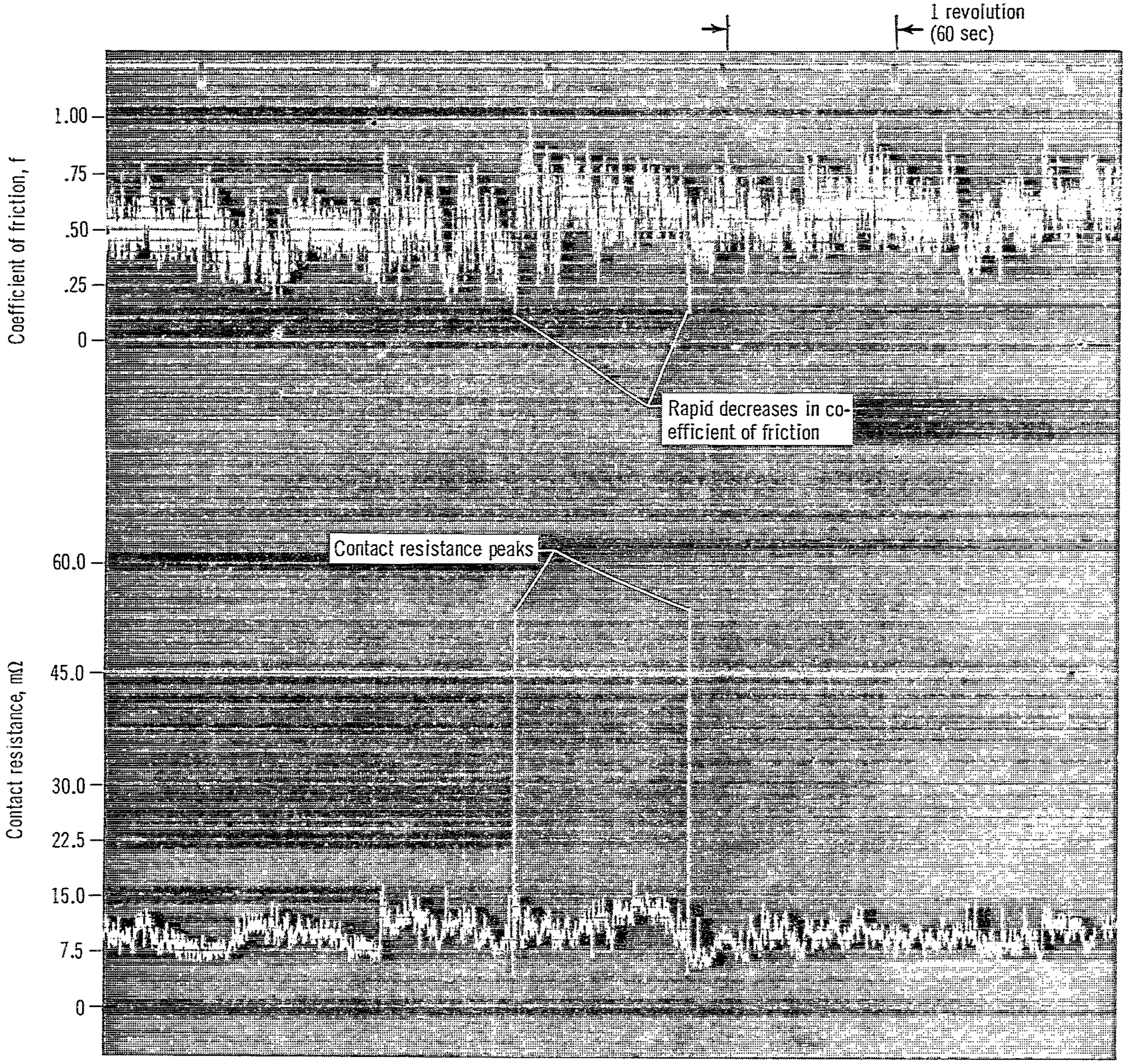


Figure 4. - Coefficient of friction and contact resistance against time for a dry tungsten against tungsten slipring assembly. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-9} to 10^{-10} torr; contact current: 33 milliamperes, 40 hertz. Revolution numbers 25 to 30.

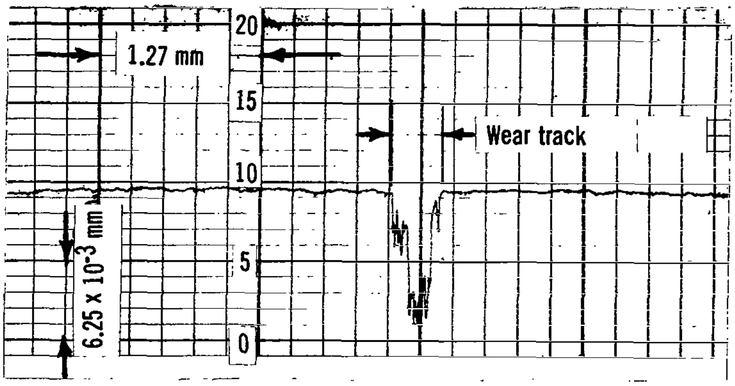


Figure 5. - Surface profile trace across wear track of dry tungsten disk run 10 hours against tungsten hemisphere. Speed, 132 millimeters per minute; load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz. Vertical magnification, 2000; horizontal magnification, 20.

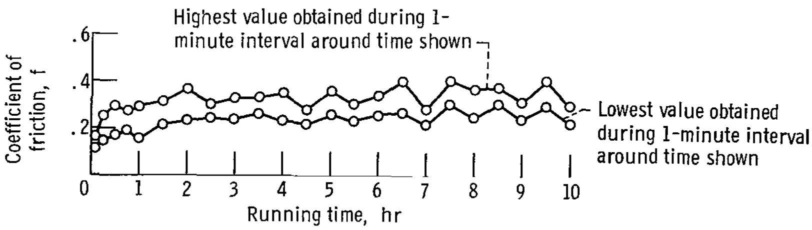


Figure 6. - Coefficient of friction against time for a tungsten disk with a mechanically applied gallium film running against a tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

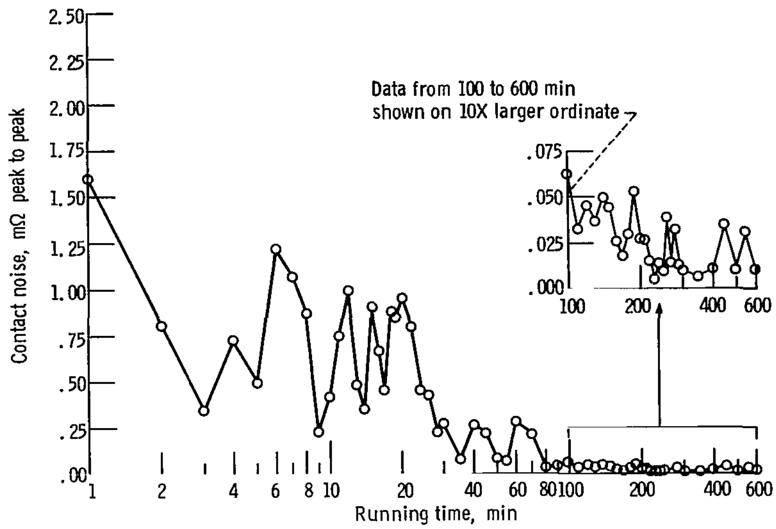


Figure 7. - Contact noise against time for a tungsten disk with a mechanically applied gallium film running against a tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

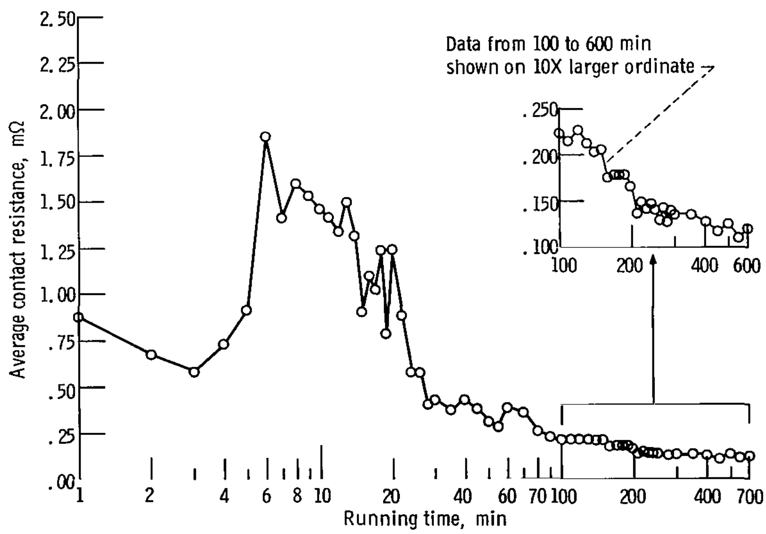
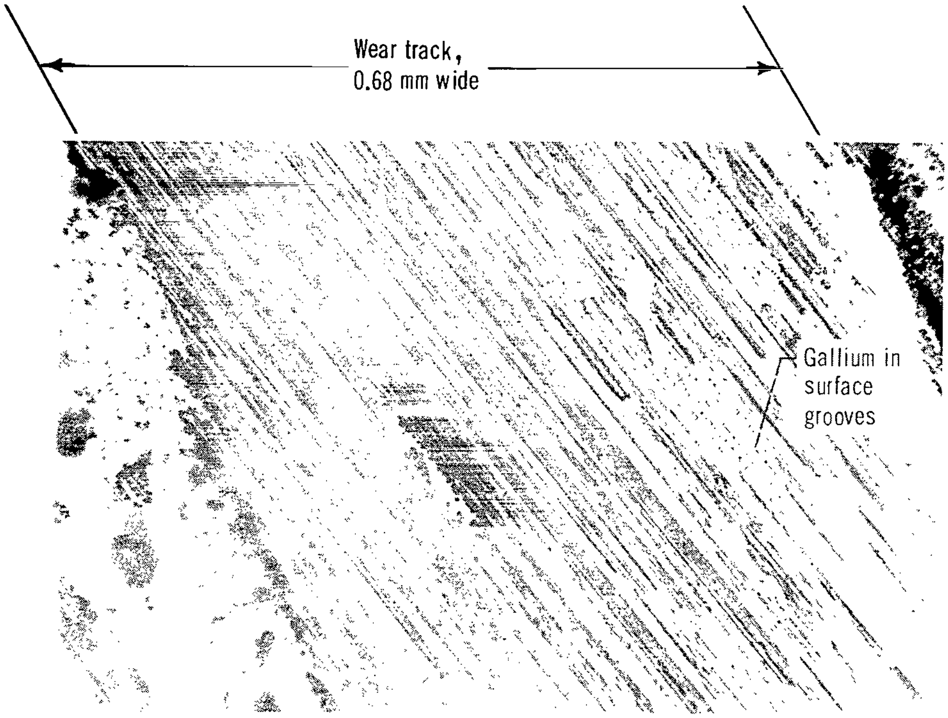


Figure 8. - Average contact resistance against time for a tungsten disk with a mechanically applied gallium film running against a tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.



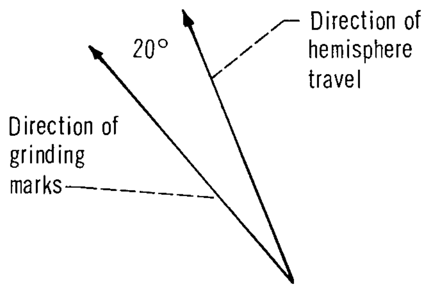


Figure 9. - Microphotograph of section of wear track on tungsten disk with gallium film that ran against a tungsten hemisphere for 10 hours. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-9} to 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

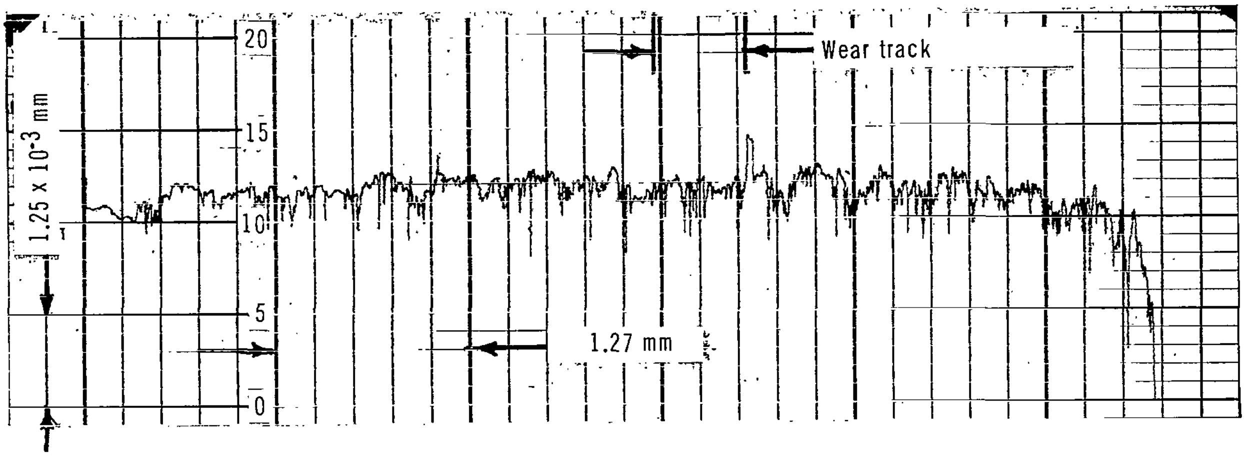


Figure 10. - Surface profile trace across wear track of ground tungsten disk with gallium film run 10 hours against tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz. Vertical magnification, 10 000; horizontal magnification, 20.

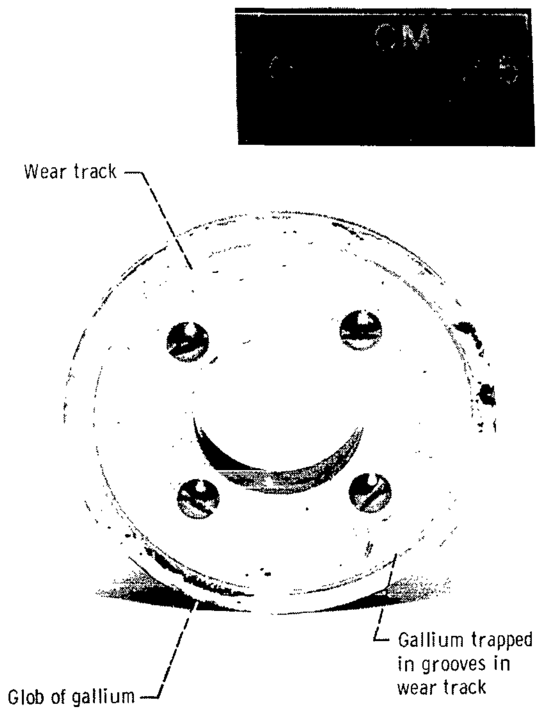


Figure 11. - Tungsten disk with gallium film after 10 hours operation against tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-9} to 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

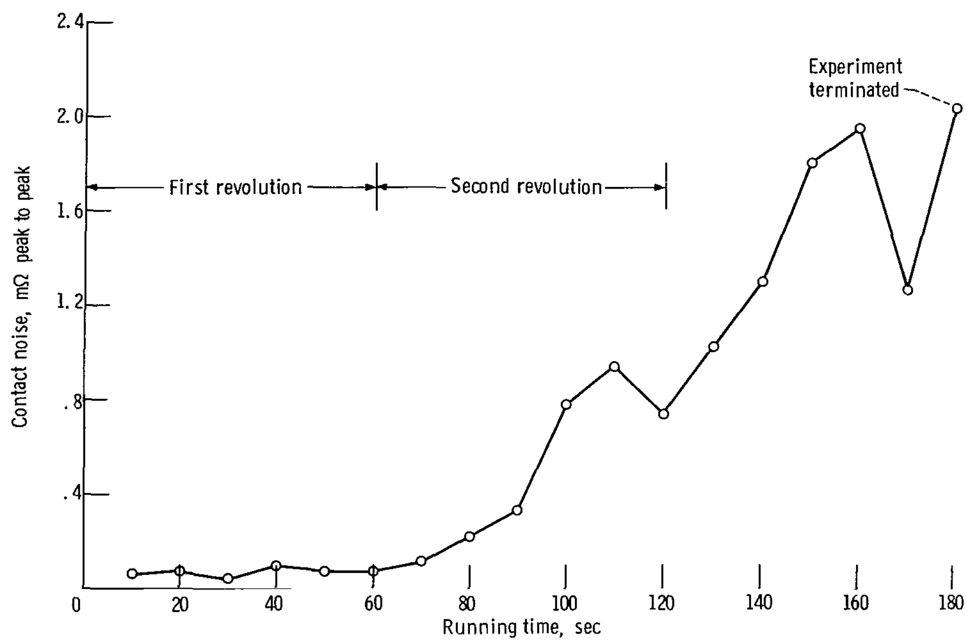
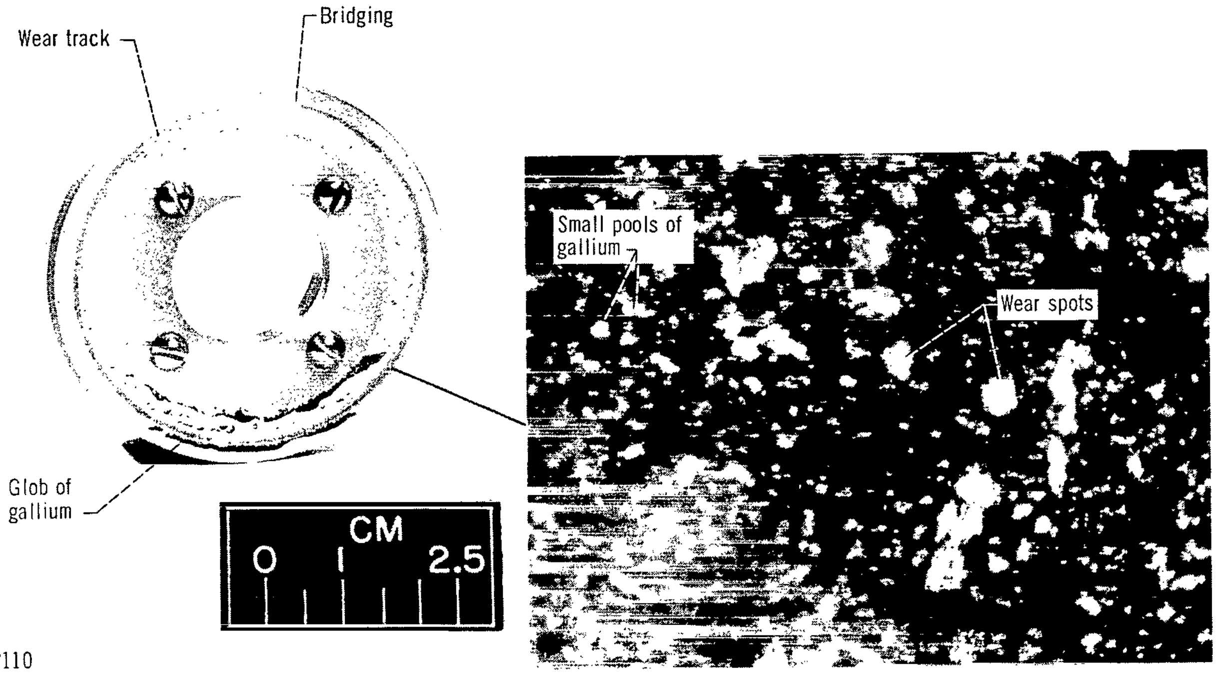


Figure 12. - Contact electrical noise against time for a tungsten disk with a mechanically applied gallium film running against a tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.



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Enlarged view of wear track. X8.

Figure 13. - Photograph of etched tungsten disk with gallium film after running 5 minutes against tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-9} to 10^{-10} torr; contact current: 33 milliamperes, 40 hertz.

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